A 3-D Thermal Analysis of the HANARO Cold Neutron Moderator Cell

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1. Introduction

Fundamental studies on a thermal analysis of a cryogenic system such as a cold neutron source (CNS) have increased significantly for a successful CNS design in cold neutron research during recent years [1,2]. A three-dimensional (3-D) thermal analysis model for the HANARO CNS was developed and used to accurately predict a temperature distribution between the hydrogen inside and the entire inner and outer surfaces of a moderator cell, whose moderator and cell walls are heated differently, under a steady-state operating condition by using the HEATING 7 code. The objective of this study is primarily to predict a temperature distribution through a heat flow in a cold neutron moderator cell heated from a nuclear heating and cooled by a cryogenic coolant. This paper presents satisfactory results of a steady-state temperature distribution in a cryogenic moderator cell. They are used to support the thermal stress analysis of the moderator cell walls and to provide a safe operation for the HANARO CNS facility.

2. Numerical Method

2.1 Design Concept of the HANARO CNS

The main part of the closed HANARO CNS consists of a cold hydrogen system connected to a hydrogen buffer tank through adequate piping and a valve manifold, and a helium refrigerator. The cold hydrogen system includes a moderator cell and a condenser with a double moderator transfer tube. The shape of the moderator cell [3] is a double cylinder with an open cavity towards the CN beam tube to remove the possibility of a cold neutron absorption and up-scattering. The moderator cell is optimized to ensure an adequate heat transfer over its entire inner surface. Its inner radius is 6.5 cm, and its height is 23.2 cm.

During the CNS steady-state operation, the moderator cell, in which the inner cavity only contains hydrogen vapor and the outer shell has liquid hydrogen, maintains at a constant two-phase mixture level and a constant hydrogen pressure. The hydrogen moderator is in a sub-cooled state at a steady-state nominal operating condition whose pressure and temperature are 1.5 atm and 21.8 K, respectively. An average hydrogen flow rate through the moderator cell is about 2.5 g/s balancing the hydrogen evaporation by nuclear heating and the liquefaction by cryogenic gas cooling. A nuclear heating in research reactors arises from the interactions with fast and thermal neutrons, a gamma-rays energy deposition in the aluminum walls of the cold neutron moderator cell and the hydrogen flowing through the cold neutron source. The total nuclear heat load on the cold source moderator cell was calculated as 629 W [4].

Aluminum alloy Al6061-T6 was selected as the structure material of the moderator cell to minimize its mass and hence to maintain the total nuclear heating rate as low as possible. The liquid hydrogen is practically adopted both as a cryogenic coolant and a neutron moderator because it possesses suitable scattering cross sections and no build up of radiation damage. The thermo-physical properties for both liquid hydrogen and gaseous hydrogen at 1.5 atm as well as aluminum alloy Al6061-T6 at the cryogenic temperature ranges of interest were taken from the literatures [5,6].

2.2 Numerical Model

The thermal analysis of the HANARO CNS should ultimately consider the 3-D effects because of a non-uniform nuclear heating and the presence of an inner cavity that partially blocks the interior flow. A 3-D thermal analysis model was developed to determine a temperature distribution over the entire inner and outer surfaces of the HANARO CNS by using the HEATING 7 code [7]. To reduce the computational load, A 3-D axisymmetric cylinder geometry was applied for a half of the cold neutron moderator cell.

3. Results

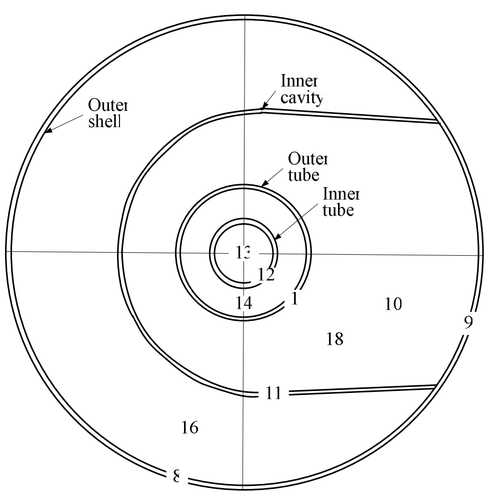
The maximum wall temperature was calculated as 50.9K which was located on the inner cavity wall of the moderator cell closest to the reactor core. The heat generation rate is maximum there since the hydrogen gas trapped inside it, which is hardly cooled due to a poor heat transfer rate. The inner cavity of the moderator cell near the CN tube had a high temperature in the range of 23.9 to 50.9 K. The minimum temperature of 21.8 K was located on the outer shell farthest from the reactor core which was opposite to the location of the maximum temperature in the moderator cell. The temperatures of the outer shell were distributed uniformly at around 22 K over the moderator cell due to the cooling by the cryogenic liquid hydrogen. The liquid hydrogen temperature near the side cavity wall was 22 K with a corresponding 40.3 K wall temperature for the inner cavity. The wall temperature of the inlet tube carrying the cryogenic liquid hydrogen from the condenser remained at about 21.8 K. The numerical results of the steady-state temperature distribution in the moderator cell are presented in Table 1 and shown in Figure 1, respectively.

4. Conclusion

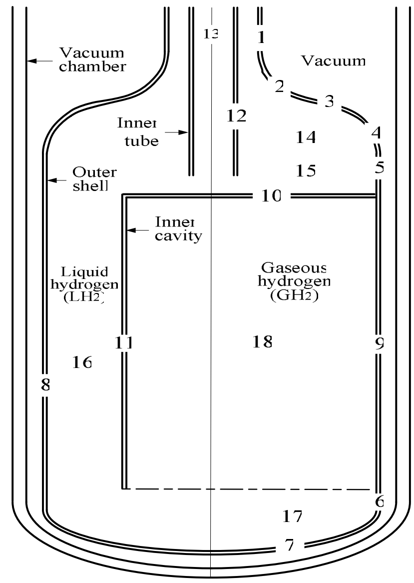
The numerical results for the moderator cell show an optimistic prediction for its temperature distribution. The temperature distribution within the moderator cell is one of the most important parameters for analyzing a cold neutron source. Consequently, such a cryogenic thermal analysis is very useful for a reliable operation limit for normal operation strategies and the safety analysis of a cold neutron moderator cell. Moreover, the temperature calculations can be used to support a thermal stress analysis of a moderator cell wall.

Table 1. Temperature distribution in the cold neutron moderator cell.

Component	Region number	Temperature distribution (K)
Outer shell wall, Al	1	21.80 – 21.95
	2	21.80 – 21.82
	3	21.82 – 21.89
	4	21.80 – 21.87
	5	21.80 – 21.87
	6	21.80 – 21.87
	7	21.80 – 21.87
	8	21.80 – 21.87
Inner cavity wall, Al	9	23.90 – 50.90
(near CN tube)	–	–
Upper cavity wall, Al	10	21.80 – 44.24
Side cavity wall, Al	11	21.86 – 40.29
Inner tube wall, Al	12	21.82 – 21.89
LH_2 in inner tube	13	21.84 – 22.00
LH_2 in upper outer shell	14	21.82 – 21.87
except inner tube	15	21.80 – 22.00
LH_2 in lower outer shell	16	21.82 – 21.96
LH_2 in bottom outer shell	17	21.87 – 22.00
GH_2 in cavity	18	21.81 – 42.16



1) xy-plane



2) yz-plane

Figure 1. Temperature distribution in the cold neutron moderator cell.

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